Photoproduction in Ultra-Peripheral Heavy-Ion Collisions

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Abstract

The strong electromagnetic fields present in ultra-peripheral collisions of heavy-ions offer a possibility to study two-photon and photonuclear collisions complementary to similar studies with lepton beams but over an increased photon energy range. This presentation[1] will give an overview of photoproduction at hadron colliders.

1 Introduction

The idea to use the strong electromagnetic fields in high energy proton-proton and nucleus-nucleus collisions to study photon-induced interactions has attracted an increased interest in recent years. Various aspects of such interactions have been discussed in presentations at earlier conferences in this series during the last ten years[2, 3, 4, 5, 6], and it is gratifying to see that an entire session is devoted to the topic this year.

This presentation will give an overview of photoproduction at hadron colliders. The focus will be on the accelerators with the highest collision energy in the world currently: the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (proton-proton and heavy-ion collisions), The Fermilab Tevatron (proton-anti-proton collisions), and the CERN Large Hadron Collider (first proton-proton collisions expected in 2008, later also heavy-ion collisions). More complete reviews can be found in Refs. [7, 8].

2 Photoproduction at hadron and electron colliders

Photon-induced interactions have been studied with lepton beams in fixed target experiments and at colliders. But photon-hadron and two-photon interactions can occur also when the lepton-beams are replaced by ultrarelativistic protons or heavy nuclei. The maximum photon energies are then restricted by the form factor of the projectile. An additional restriction on the "useful" photon energy spectrum comes from the requirement that there be no other, hadronic interactions in the same event. The presence of a form factor, when translated into impact parameter space, roughly corresponds to a cut on the minimum impact parameter of $b > R$, where R is the radius of the projectile, while the requirement that there be no accompanying hadronic interactions is more restrictive and corresponds to $b > 2R$. The presence of a form factor also means that only interactions with low-virtuality photons can be studied. Despite these limitations, the very high collision energies of current hadron colliders lead to useful photon energies exceeding those at HERA and LEP, for example.

Since the intensity of the electromagnetic field is proportional to the square of the charge of the beam particle, photon-induced interactions are enhanced by up to a factor Z^2 (Z is the atomic number of the ion) in heavy-ion collisions.

The spectrum of equivalent photons in pp and heavy-ion collisions are shown in Fig. 1. The luminosity scale on the y-axis should be interpreted with care, in particular for pp

collisions, since at the maximum beam luminosities there are usually several overlapping events in a single bunch-crossing. Overlapping events may preclude a clean separation of the photon-induced reactions and the effective photon luminosities might therefore be lower.

A major difference between lepton- and hadron-beams is that with hadron beams a certain reaction channel can often proceed both via a strong interaction as well as through an electromagnetic interaction. One illustrative example is the production of two (heavy) quarks. At hadron colliders, this can happen through a purely electromagnetic (two-photon) process, $\gamma+\gamma\rightarrow Q\overline{Q}$. It can also proceed via photon-gluon fusion $\gamma+g\rightarrow Q\overline{Q}$ and gluon-gluon fusion $g+g\rightarrow Q\overline{Q}$. The two-gluon fusion production is the dominant production mechanism for pairs of b and c quarks. Estimates show that the ratios of the cross sections for the three processes in Pb+Pb interactions at the LHC are roughly 1:10^3:10^6[9]. This is a consequence of the different coupling strengths (strong vs. electromagnetic) and the cut-offs introduced by the form factors. The cross section for purely electromagnetic production of a pair of heavy quarks is thus only a fraction $\sim 10^{-6}$ of the cross section for the dominating production mode through two-gluon fusion. The large difference in cross section is one reason why special trigger and analysis techniques are needed to study photon-induced processes at hadron colliders.

One should note, however, that some ultra-peripheral reaction channels have very high cross sections, in some cases even higher than the total hadronic cross section. This is the case for two-photon production of e^+e^--pairs and exclusive production of ρ^0-mesons in high energy heavy-ion collisions.

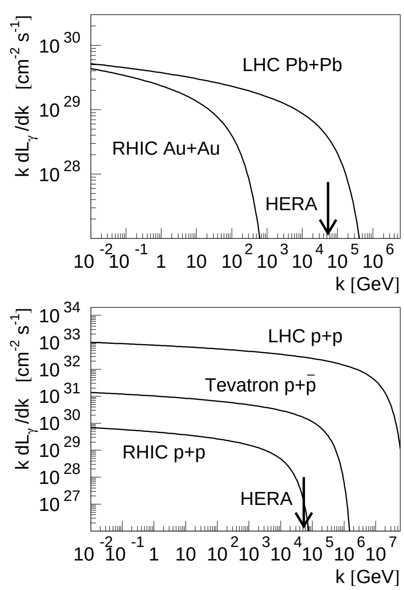

Figure 1: Equivalent photon luminosity (the photon spectrum dn/dk multiplied by the beam luminosity) in heavy-ion (top) and proton-proton collisions (bottom). The photon energy, k, is calculated in the rest frame of one of the projectiles. The arrow shows the maximum photon energy in $e+p$ collisions at HERA. The spectra are calculated as described in[9].

3 The physics of ultra-peripheral collisions

One can distinguish two classes of ultra-peripheral collisions: Interactions in which both nuclei/protons remain intact (e.g. two-photon interactions and coherent photonuclear production of vector mesons, $\gamma+A\rightarrow V+A$) and interactions in which the "target" nucleus/proton breaks up (e.g. photonuclear production of jets or heavy quarks, $\gamma+A\rightarrow jet+X$ or $\gamma+A\rightarrow Q\overline{Q}+X$).

The two types of interactions are charac-

terized by one or two rapidity gaps void of particles between one or both beams and the produced particles.

The first class of events can be either purely electromagnetic (two-photon interactions) or photonuclear. Two-photon interactions with heavy-ion beams is a valuable probe of strong field QED. The effective coupling is enhanced by a factor of Z for photons emitted from one of the beam nuclei, and this increases the importance of higher-order Coulomb corrections. Two-photon processes are, furthermore, the leading source of beam-loss at heavy-ion colliders through the creation of so called bound-free pairs, i.e. two-photon production of an e^+e^-–pair, where the e^- binds to one of the nuclei. The capture of an electron alters the rigidity of the ion and leads to a different deflection by the accelerator magnets, and this results in the loss of the ion from the beam[10].

The interest in exclusive and inclusive photonuclear of photon-hadron collisions derives mainly from the sensitivity of the cross section to the parton distribution functions. The exclusive production of heavy vector mesons has been modelled as the colorless exchange of two gluons, with the cross section being proportional to the gluon distribution squared. Photoproduction of heavy quarks is dominated by the direct, leading-order photon-gluon fusion process. The cross section is therefore a direct measure of the nuclear or nucleon gluon distribution. Photon-induced di-jet production is a probe of the target parton distribution functions and the partonic substructure of the photon[7].

Some phenomena in ultra-peripheral hadron interactions cannot be studied with electron beams. This includes interference between the target and emitter configurations and the possibility to search for the Odderon through Odderon+Pomeron fusion.

The exclusive production of vector mesons has attracted considerable interest both experimentally and theoretically recently and will be discussed in more detail below.

Model	ρ^0 [mb]	J/Ψ [μb]
KN [11]	590	290
GM [12]	876	476
IKS [13]	478, 483	304, 274
FSZ [14]	934	168, 212

Table 1: Calculated cross sections for exclusive vector meson production in Au+Au collisions at RHIC. The two values for IKS are for two different parameterizations of the dipole cross section. The higher FSZ value for J/Ψ is without shadowing.

At high photon energies and low virtualities, a photon may fluctuate into a vector meson and remain in that state for times that are long compared with the times required for the photon to pass typical nuclear distances (~ 10 fm). While in the vector meson state, the photon may scatter diffractively off the target nucleus and emerge as a real vector meson.

The total cross section for exclusive vector meson production can be calculated as the convolution of the photonuclear cross section, $\sigma_{\gamma A}$, with the equivalent photon spectrum, dn/dk. On differential form, this becomes

$$\frac{d\sigma(A+A \to A+A+V)}{dy} = k_1 \frac{dn_\gamma}{dk_1} \sigma_{\gamma A}(k_1) + k_2 \frac{dn_\gamma}{dk_2} \sigma_{\gamma A}(k_2),$$

where y is the rapidity of the produced vector meson and k_1 and k_2 are the photon energies for the two target-emitter configurations. These are related to the rapidity and mass of the vector meson through $k_1 = (M_V/2)\exp(+y)$ and $k_2 = (M_V/2)\exp(-y)$. At mid-rapidity, $k_1 = k_2$ and the contributions from the two terms are equal.

The cross sections for coherent and exclusive vector meson production in ultra-peripheral collisions have been calculated by four groups[11, 12, 13, 14]. Examples of cross sections for one light (ρ^0) and one heavy (J/Ψ) vector meson in Au+Au and Pb+Pb interactions at RHIC and LHC, respectively, are given in Tables 1 and 2. There is broad agreement, but individual cross sections may

Model	ρ^0 [b]	J/Ψ [mb]
KN [11]	5.2	32
GM [12]	10.1	41.5
IKS [13]	4.0, 4.4	26.7, 26.3
FSZ [14]	9.5	14, 85

Table 2: Calculated cross sections for exclusive vector meson production in Pb+Pb collisions at the LHC. The two values for IKS are for two different parameterizations of the dipole cross section. The higher FSZ value for J/Ψ is without shadowing.

differ by up to a factor of 2 between different calculations.

The calculations by Klein and Nystrand[11] are based on scaling the measured $\gamma p \rightarrow Vp$ cross sections to $\gamma A \rightarrow VA$ using the Glauber model (assuming $\sigma_{tot}(VA) = \sigma_{inel}(VA)$). The calculations by Goncalves and Machado[12] and by Ivanov, Kopeliovich and Schmidt[13] are based on the QCD color dipole model. There are not enough details given in [13] to determine where the difference between the two models stems from; a possibility is different parameterizations of the dipole cross section.

The cross sections for J/Ψ calculated by Strikman, Tverskoy and Zhalov[14] were obtained from a Glauber model, where the photon-nucleon cross sections have been modified to include the effect of shadowing from the leading twist mechanism. Results with and without shadowing are given. The cross sections for ρ^0 in [14] are calculated from a Glauber model including non-diagonal matrix elements (Generalized Vector Meson Dominance). The input photon-nucleon cross sections were obtained from parameterizations based on the soft Pomeron model, and the magnitude of the non-diagonal elements where extracted from fits to data on $\gamma + Pb \rightarrow \rho + Pb$ at $E_\gamma = 6.3$ GeV.

The photon spectra in [11, 12, 14] are calculated in impact parameter space with somewhat different requirements but in all cases effectively corresponding to the exclusion of events with $b < 2R$. The differences in the photon spectra are therefore not expected to contribute significantly to the differences in the cross sections.

4 Results on ultra-peripheral collisions

The experimental studies of ultra-peripheral collisions have so far focussed on exclusive and coherent particle production. This has the advantage that there are rapidity gaps on either side of the produced state and also that the final state will have a very low total transverse momentum, p_T, consistent with the coherent couplings to both beam particles. For heavy nuclei, this means p_T in the range of $50 - 100$ MeV/c. Tagging on the very low p_T provides a powerful background rejection if all particles emitted from the collision are reconstructed.

A key challenge in these studies is the implementation of an efficient trigger. Since the outgoing protons or nuclei are not tagged, the trigger has to be sensitive to a low multiplicity (as low as two charged particles) around mid-rapidity while keeping the background rates low. In ultra-peripheral heavy-ion collisions, where the probability for exchanging an additional, soft photon is high, it has been found that triggering on events where one or both of the nuclei break up because of Coulomb excitation can reduce the trigger background rates significantly. The additional photon(s) may excite the nucleus (e.g. to a Giant Dipole Resonance) and the de-excitation leads to break up and the emission of one or a few neutrons in the direction of the beam.

Exclusive production of vector mesons and di-lepton pairs have been studied by the STAR[15] and PHENIX[16] collaborations at RHIC, and two-photon production of e^+e^-–pairs have been studied by the CDF Collab-

oration at the Tevatron[17]. These results have also been presented at this conference. There are currently plans to study ultra-peripheral collisions in three of the LHC experiments (ALICE, ATLAS, CMS). ALICE is the dedicated heavy-ion experiment at the LHC and the possibilities for studying ultra-peripheral collisions with ALICE are described in the ALICE Physics Performance Report[19]; they will be summarized below. The main focus is on exclusive production of vector mesons, but the possibilities for studying photon-gluon interactions are also discussed. The plans to study ultra-peripheral collisions in CMS are discussed in the CMS Physics Technical Design Report, and they have also been presented at this conference[18].

The main charged particle tracking detector in ALICE is the Time-Projection Chamber (TPC), covering the pseudo-rapidity interval $|\eta| \leq 0.9$. This is supplemented by an inner tracking system consisting of 6 layers of Si-detectors. Particle identification is obtained from the energy loss in the TPC and from the Time-of-Flight (ToF) detector surrounding the TPC. Electrons can be identified in the transition radiation detector, located between the TPC and the ToF.

A low-multiplicity trigger is provided by the Si-pixel and ToF detectors. The ToF trigger logic allows the requirement on multiplicity to be combined with a "topology-cut" to reject cosmic ray events and reduce the number of fake triggers. The ToF also serves as a pre-trigger for the transition radiation detector, which provides online electron identification.

The ALICE mid-rapidity tracking and trigger detectors can be used to study exclusive vector meson production of $\rho^0 \rightarrow \pi^+\pi^-$, $J/\Psi \rightarrow e^+e^-$ and $\Upsilon \rightarrow e^+e^-$. The estimated rates during one month of heavy-ion running are shown in Table 3.

The heavy vector mesons can also be studied through their decay into dimouns in the ALICE muon arm. The arm covers the range $2.5 \leq \eta \leq 4.0$ in pseudo-rapidity and provides a low-level trigger for muons. The expected rates for the muon arm are somewhat lower than for the central barrel.

Meson	Geometrical Acceptance	Rate (per 10^6 s)
ρ^0	7.9 %	$2 \cdot 10^8$
J/Ψ	16.4 %	150 000
$\Upsilon(1S)$	23.6 %	400 – 1400

Table 3: Estimated rates for exclusive vector meson production within the ALICE central acceptance ($|\eta| \leq 0.9$) for a one month (10^6 s) run at the design Pb+Pb luminosity. From [19].

The ZDCs in ALICE are located too far from the interaction point to be included in the normal lowest level trigger, but could be used for triggering on ultra-peripheral collisions in special runs.

5 Summary and outlook

The idea to study the production of e^+e^-–pairs in ultra-peripheral nuclear collisions goes back to the 1930s. The first experimental indication of two-photon interactions with hadronic beams appears to have been the observation of $\mu^+\mu^-$–pairs in proton-proton collisions at the ISR[20].

Two-photon production in heavy-ion collisions was subsequently studied in fixed target experiments at the Bevalac, the BNL AGS, and the CERN SPS.

The feasibility of studying photon-induced processes at colliders has been demonstrated by experiments at RHIC and the Tevatron. The measured cross sections have been found to be in general agreement with expectations, but the statistics has so far been limited.

The situation at the LHC should be more advantageous because of the strong increase in the cross sections with energy. This, together with improved trigger capabilities in the experiments, should give higher statistics

for many interesting ultra-peripheral collision final states. The increased collision energies also imply that lower ranges of Bjorken–x are probed in photon-induced processes.

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